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Impact of Terrain Features for Tactical Network Connectivity

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Executive Summary

A Mobile Ad Hoc Network (MANET) faces many challenges inherent to wireless networks (e.g., addressing, routing, location management, and security). Additional complications arise from the lack of infrastructure and central management. In particular, the performance of a MANET is influenced strongly by its ability to cope with topology changes arising from node mobility. The changing connectivity between nodes can be caused by numerous environmental features, including atmospheric absorption and interference caused by line-of-sight (LOS) obstruction.

We show that insights into static and mobile network performance can be gained through an analysis based on the average features of terrain. We find that there are stable metrics—the probability of link closure ($\bar{p}$) and the link-state correlation length ($\bar{\lambda}$)—that depend primarily on average features of the terrain and can be used to forecast aspects of network performance. These metrics enable the characterization of network performance in different operational environments, give insights into routing algorithm selection, and provide the ability to quantify performance predictions, all of which can inform technology development and testing. We show how terrain features affect changes in link state under mobility, specifically the probability that pairs of nodes remain connected. We find that this probability is nearly independent of the number of nodes in the network. In other words, while increasing the number of nodes in challenging environments improves the probability that two nodes can be initially connected, it does not improve the probability that a chosen path will remain connected. We provide a visualization method (link closure maps) that permits a quick, qualitative comparison of expected (static) network connectivity in different terrain conditions.

We also apply similar methods to mobile networks. Dynamic networks exhibit changes to the link-state matrix at a rate that is approximately independent of node separation but that depends on terrain type.

Contents

1. Introduction

A Mobile Ad Hoc Network (MANET) faces many challenges inherent to wireless networks (e.g., addressing, routing, location management, and security). Additional complications arise from the lack of infrastructure and central management. In particular, the performance of a MANET is strongly influenced by its ability to cope with topology changes arising from node mobility. The changing connectivity between nodes can be caused by numerous environmental features, including atmospheric absorption and interference caused by line-of-sight (LOS) obstruction. Basic networking issues become increasingly complicated with mobility (Shrestha and Tekiner 2009; Manfredi, Hancock, and Kurose 2008; Conti and Silva 2007).

One method of minimizing the negative effects of such complications is through the appropriate selection of routing algorithms. Two basic classes of routing algorithms used in MANETs are based on proactive and reactive models (Mbarushimana and Shahrabi 2007). Proactive routing updates the routing table on a set timetable that is independent of offered traffic. Reactive routing updates the routing table only when needed because traffic is present. Some theoretical work has been done on incorporating mobility and terrain into these algorithms (Kum 2010; Chin 2005; Roobol 1993). Generally, an informed expectation of network behavior with mobility in a given environment will allow one to identify an optimal algorithm for routing.

That said, the primary goal of this analysis is not to optimize algorithms, but to provide a framework for characterizing the environment. We see quantification of the effects of the environment as a useful preliminary step to designing a networking waveform. Here, we attempt to understand the fundamental rates of change in link state as node mobility occurs over non-flat terrain and to describe these changes in terms of the characteristic parameters of the terrain.

For the analysis in this document, we chose three sites with different terrain features: Charlottesville, Virginia; Fort Huachuca in Southeast Arizona; and White Sands Missile Range (WSMR), New Mexico. Using terrain elevation data from these sites, we calculated the LOS visibility between mobile nodes. We considered LOS visibility as a surrogate for connectivity and analyzed the link-state matrix for the static and the displaced nodes. This analysis is a first step to a complete engineering model of connectivity and is accurate when diffraction, attenuation, and Fresnel zone effects are insignificant.

Qualitatively, visibility is acceptable when networks operate over flat terrain. Under our simple LOS model of connectivity, mobility has little impact in such an environment.

In practice, the effect of mobility is an upper bound on network performance. Issues such as multi-path interference or Doppler shifting may degrade a signal that is transmitting during mobility over flat terrain. We have defined metrics that enable the *quantitative* characterization of the effect of non-flat terrain on network behavior with and without mobility. We have identified predictable impacts on the rate of change of link state and the likelihood of network connectivity of pairs of nodes based on terrain features. Not only are such properties of interest predictable, but these predictions can also be made using average features of the terrain.

The ability to forecast network performance based on knowledge of the terrain will have implications for the design and management of mobile wireless networks (Du, Faber, and Gunzberger 1999). Developing these implications in detail is beyond the scope of this document. However, network latency, power management, expected path length (with its implications for throughput), average expected number of subnets, and necessary node density for effective operation are areas that are likely to be informed by the terrain considerations outlined here (Shrestha and Tekiner 2009).

2. Methodology and Results

For this analysis, we selected three geographically distinct regions of interest, which span a variety of terrain types. The first, Charlottesville, Virginia, is an area of rolling hills in the Piedmont region of central Virginia; the second, Fort Huachuca, is in Southeast Arizona; and the third, WSMR, is in New Mexico. Fort Huachuca and WSMR are areas of mountainous desert terrain that have been used by the Department of Defense (DoD) to test the performance of MANET radios.

The topographical maps in Figure 2-1(a)–(c) show that the three regions display different characteristics. Around Charlottesville, the range in elevation is small ($< \pm 125$ m), but the terrain has a high-frequency structure (length scale on the order of a kilometer or less) with amplitude that exceeds expected antenna heights. Fort Huachuca shows larger total elevation change but with a large-amplitude, low-frequency terrain structure. The WSMR terrain has one dominating feature—a ridge that divides the site—but is otherwise relatively featureless.

North-South (blue) and East-West (green) line profiles cut through the center of each region and are shown in Figure 2-1(d)–(f). We display such curves to show that one can use simple observation to gain intuition regarding the various features of a network established in each environment. For example, while the Charlottesville region is far from flat, it is approximately topographically invariant on the scale of 1 km. Fort Huachuca, on the other hand, displays a concave, bowl-like structure that will benefit communications between antennae located on the perimeter. In WSMR, the ridge increases the likelihood of orphaned nodes or the formation of multiple networks. This line-profile analysis provoked a further question: how can detailed terrain analysis better inform performance predictions?

For an in-depth analysis of network formation and functioning in the three regions, we used terrain data from the National Elevation Dataset (NED) provided by the U.S. Geological Survey (USGS). These data have resolutions of 1 m in elevation, and 1 arcsec (~30 m) laterally. We assumed that the radios would be mounted in vehicles and that parts of the terrain would be inaccessible to these vehicles due to maneuverability limitations. Thus, nodes were excluded from regions where the local grade exceeded 45 deg. Also excluded were any regions of lesser grade but entirely surrounded by inaccessible regions. Figure 2-2 shows the regions with the inaccessible areas colored in black. Less than 5% of the area was removed based on this accessibility criterion.

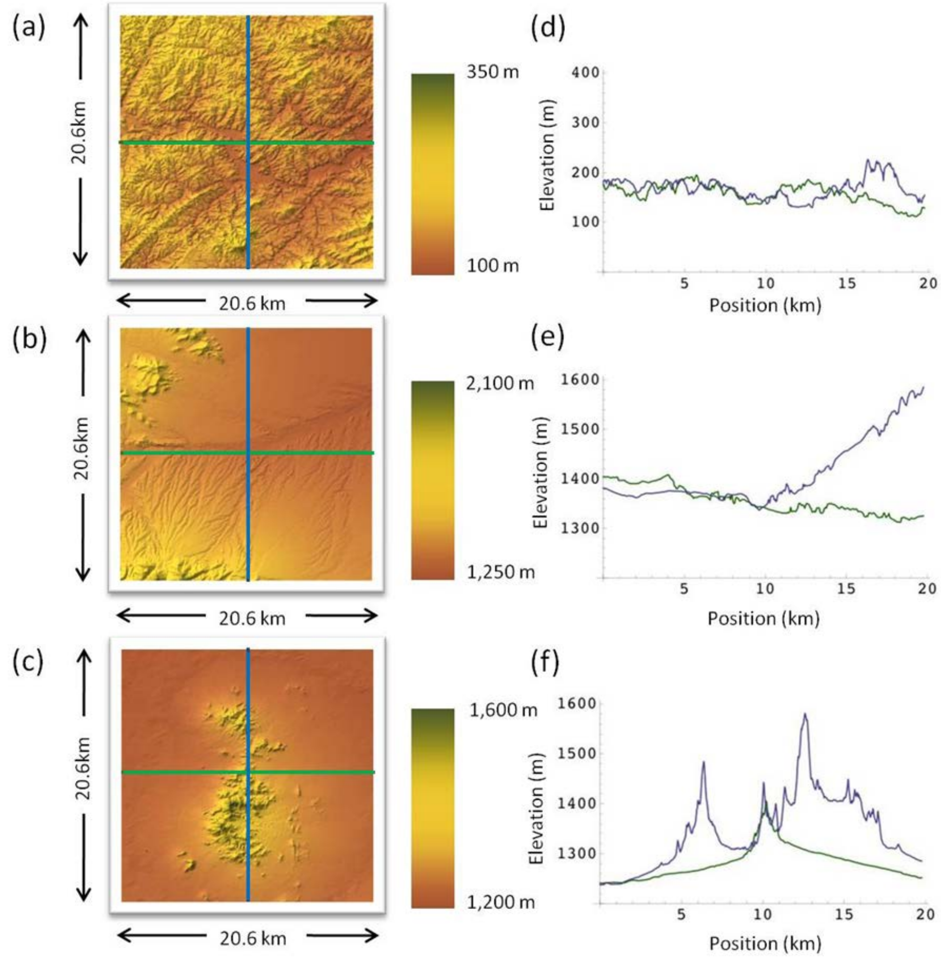


Figure 2-1. The Topographical Maps of the Areas under Analysis

Note for Figure 2-1: (a) Charlottesville, Virginia, (b) Fort Huachuca, Arizona, and (c) WSMR, New Mexico. North-South (blue) and East-West (green) line profiles are cut across each region ((d), (e), (f)).

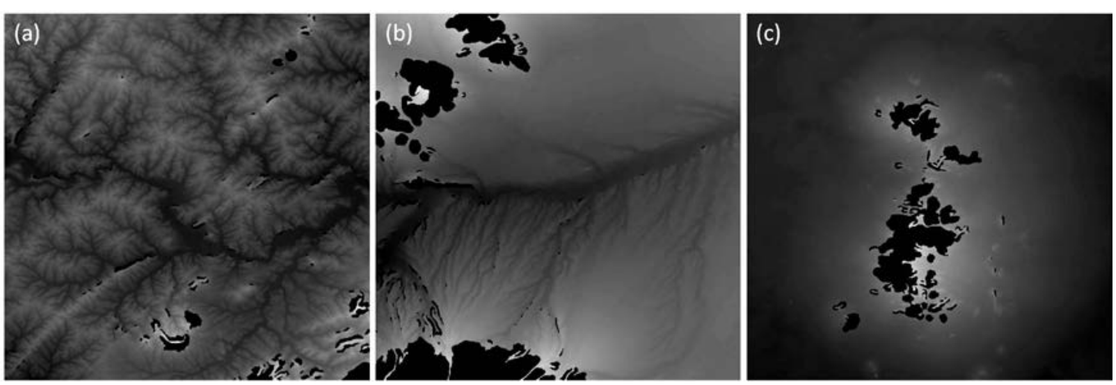


Figure 2-2. A Gray-Scale Topographical Map of
(a) Charlottesville, Virginia, (b) Fort Huachuca, Arizona, and (c) WSMR, New Mexico

Note for Figure 2-2: The blacked-out regions indicate inaccessibility by ground vehicle. These points were not used in any of the calculations.

For the accessible areas, we modeled link closure (using LOS visibility as a proxy) between pairs of points to understand the likelihood of point-to-point visibility in each site at a given range. We assumed antenna heights of 3 m and performed pairings only between the maximum and minimum elevation point in a square of 4 × 4 data points and the maximum and minimum elevation points in every other square of the same dimension within a circular cutout of the selected region (to reduce the number of necessary calculations). We performed a Voronoi tessellation of the area and assigned the color of each tile as the average of visibility to points within a range bin (Du, Faber, and Gunzberger 1999). Additional details are provided in Appendix A. Figure 2-3 shows the resulting color maps of link closure in each of the three regions, with range bins of 0–2 km, 2–8 km, and 8–16 km.

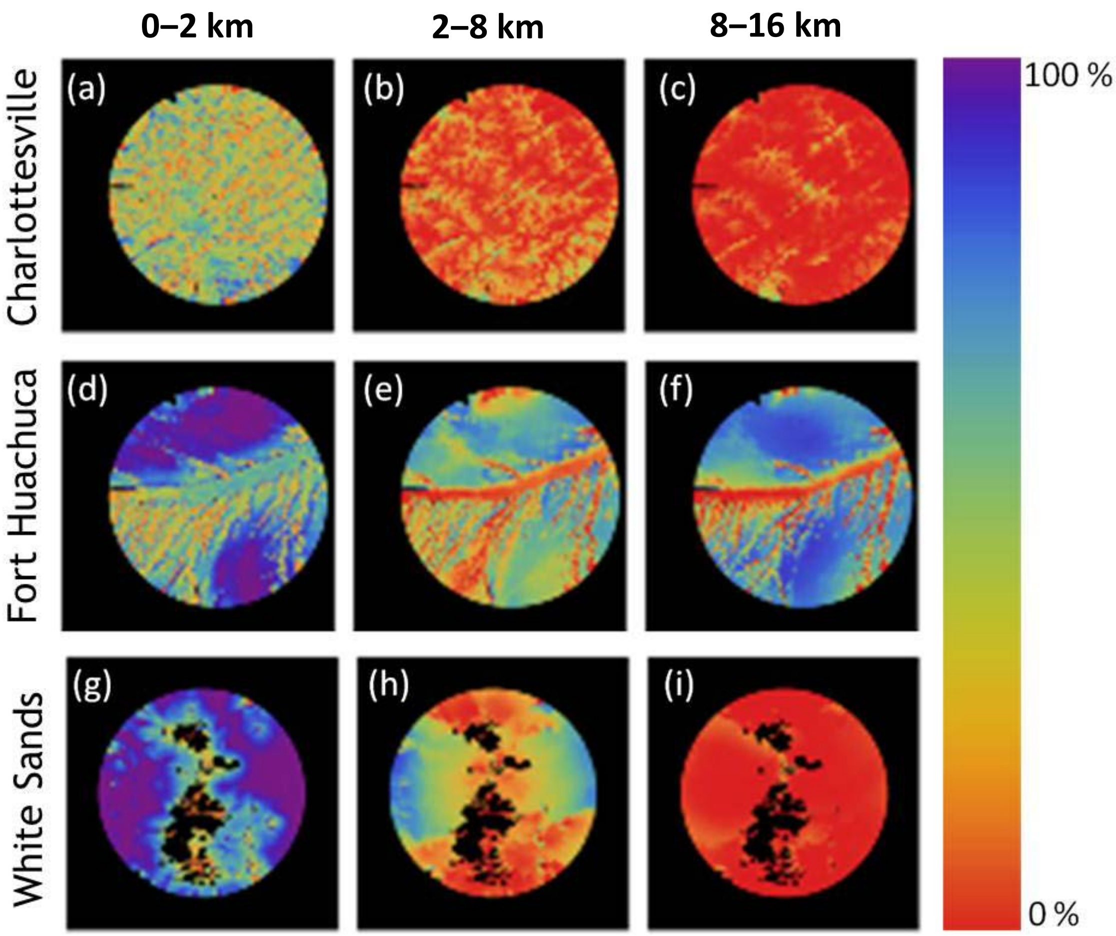


Figure 2-3. Link Closure (Based on LOS) Calculated Using Terrain Maps at 30-m Intervals Throughout a Variety of the Regions of Interest

Note for Figure 2-3: (a)–(c): Charlottesville; (d)–(f): Fort Huachuca; (g)–(i): WSMR. The maps were created for three different range bins: 0–2 km, 2–8 km, and 8–16 km. A color scale indicates percentage of surrounding points with which the point potentially has connectivity. Black indicates the regions that were filtered out of the analysis because terrain grade prevented vehicle accessibility.

Consider a green point in Figure 2-3(a). This location was colored green because for all other points within 2 km of the green point, 50% have LOS connectivity with the green point under consideration and the other 50% were blocked by some terrain feature for an antenna height of 3 m. Visual comparison of Figure 2-1 and Figure 2-3 shows a correspondence between the main terrain features in Figure 2-1 (e.g., the arroyo in Figure 2-1(b) and the ridge line in Figure 2-1(c)).

The effects of the terrain are readily observable. For Charlottesville, link closure is poor even at short ranges and collapses quickly as range increases due to the high-frequency structure (the rolling hills). For Fort Huachuca, we see the effects of the low-frequency structure (an arroyo) across the middle of the site, where visibility is the worst, and an improvement in visibility with range greater than ~8 km due to the concave structure. For WSMR, the ridge causes visibility to decrease steadily with range.

To explore the behavior of link closure with distance, we computed the probability of link closure as a function of distance between pairs of nodes. We introduce the values of $\bar{p}(d)$, the averaged fraction of closed links as a function of separation, d, and $\bar{q} = 1 - \bar{p}$, the averaged fraction of open links. (Note that $\bar{p}$ can also be interpreted as the average *probability* of link closure.) Figure 2-4 shows the average probability of link closure as a function of distance for the three regions. These metrics may be sufficient to characterize the average performance of a static ad-hoc network; however, to inform the behavior of a mobile network, we must account for the impact of mobility with an understanding of the length scale over which link state varies. In the following discussion, we describe the methodology we used to analyze this behavior.

We note that for Charlottesville and Fort Huachuca, $\bar{p}(d)$ shows relatively little change for node separations greater than 2 km. If a region has truly constant values for $\bar{p}(d)$, a simple mathematical model can be used to describe the behavior of the network under node mobility. Link opening and closure with mobility can be modeled in terms of rate equations or as a birth-death process (a continuous time Markov process where transitions are independent events limited to births and deaths) (Cinlar 1975). We will show that this simple model captures important features of network behavior.

In such a process, at a given node separation of d, the probability of a closed link remaining closed when one node moves a distance of δ follows an exponential function of the form

$$p_{1-1}(\delta)|_d \propto e^{-\delta/\bar{\lambda}(d)}, \tag{2-1}$$

where $\bar{\lambda}(d)$ is the node-separation-dependent characteristic length parameter that is used to fit Eq. 2-1 to the observed data. Thus, λ, the link-state correlation length, is the characteristic distance that a node will have to be displaced for the link to have a significant

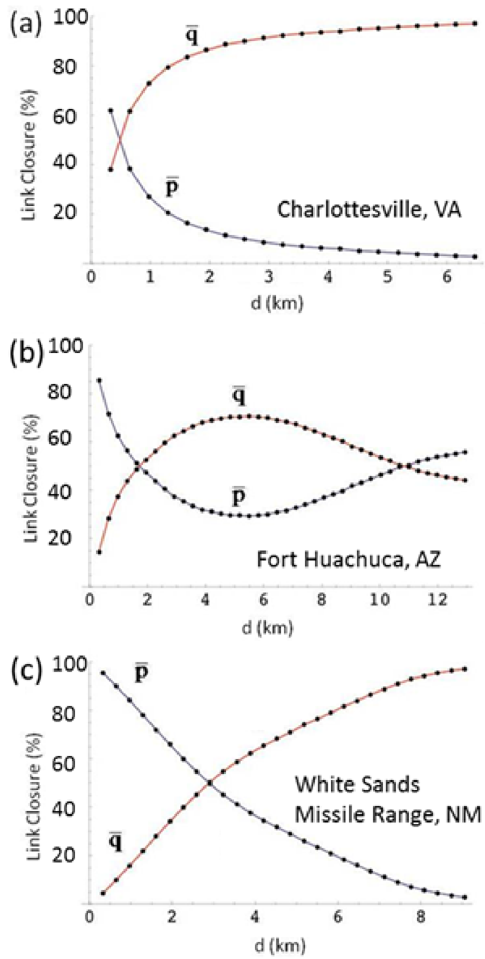


Figure 2-4. The Average Probability of Link Closure as a Function of Distance for the Three Regions

Note for Figure 2-4: The values $\bar{p}$ and $\bar{q} = 1 - \bar{p}$ were calculated for the three regions of interest by binning the percentage of closed links for a random laydown in each environment by the distance between nodes. The average value for each distance is shown. In Charlottesville (a), the values for $\bar{p}$ and $\bar{q}$ quickly drop to a slowly changing value, indicating little sensitivity to range after a few kilometers. In Fort Huachuca (b), the unique bowl-like shape of the environment causes an initial decrease in average connectivity that is followed by an increase with range. In WSMR (c), the average connectivity decreases continuously, approaching 0 around a range of 9 km, beyond which the points are separated by the ridge.

probability (one e-folding, or 37%) of changing state. To determine this characteristic length scale, we performed a Monte Carlo simulation of link state following node displacement. Initially, the nodes were randomly laid across the terrain, and the link state and distance (d) were noted. One of the nodes was displaced a random vector distance, δ, with the magnitude restricted to less than $d/2$. The link state was then recalculated. We binned the resulting link states by d and plotted the percentage of each link transition (open-open, closed-closed, open-closed, closed-open) as a function of the magnitude δ. Figure 2-5 shows an example of the fit for initially closed links opening.

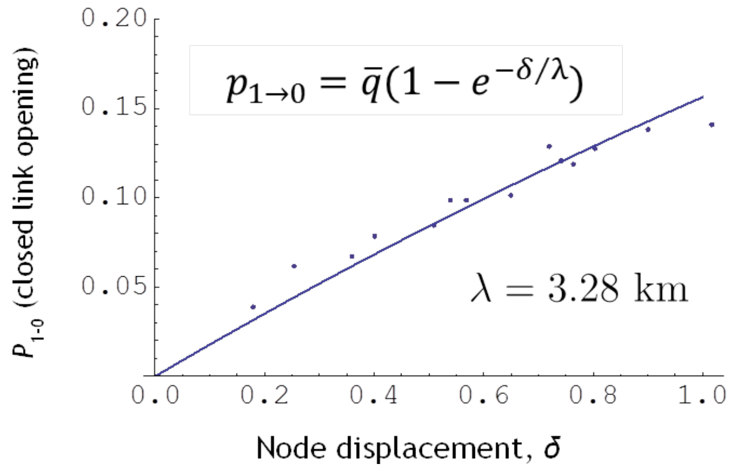


Figure 2-5. Example of Determining λ from Small Displacement for Two Points Separated by 2.5 km before Small Displacement in Fort Huachuca

Note for Figure 2-5: The equation for the probability of a transition from 1→0 is expanded to third order and fit the data.

From the Monte Carlo data used for these plots, the probability that a closed link opens as δ increases is approximately described by the form

$$p_{1-0}(\delta)|_d = \bar{q}|_d(1 - e^{-\delta/\lambda|_d}). \tag{2-2}$$

From these data and the values of $\bar{p}$ (as previously determined), we estimated λ at each of the binned values of d by fitting the curves for small values of δ. The results are plotted in Figure 2-6. The robustness of this approach was ensured with two checks: (1) we determined that the uniform sampling of magnitude and direction for δ did not influence the value of λ, and (2) we independently estimated the value of λ using the 0-1 and 1-0 data and confirmed that the values were the same.

As noted previously, for Charlottesville and Fort Huachuca, $\bar{\lambda}(d)$, is nearly constant. $\bar{\lambda}$ shows ±20% variation at the WSMR site as d varies between 2 and 8 km. The use of a single characteristic length, independent of node separation, is clearly valid for Charlottesville and Fort Huachuca and may be useful when applied to WSMR. The Charlottesville and Fort Huachuca curves for $\bar{p}$ and $\bar{q}$ also vary modestly with d over the range of interest for tactical mobility. From the calculated distributions of $\bar{p}$, we also conclude that $p(d) \cong \bar{p}$ is a reasonable approximation for most internode distances, at least for Charlottesville and Fort Huachuca. This assumption enables a description of network performance characteristics in terms of the averaged features of the system LOS over the terrain and simplifies the rate equation or Markov approach.

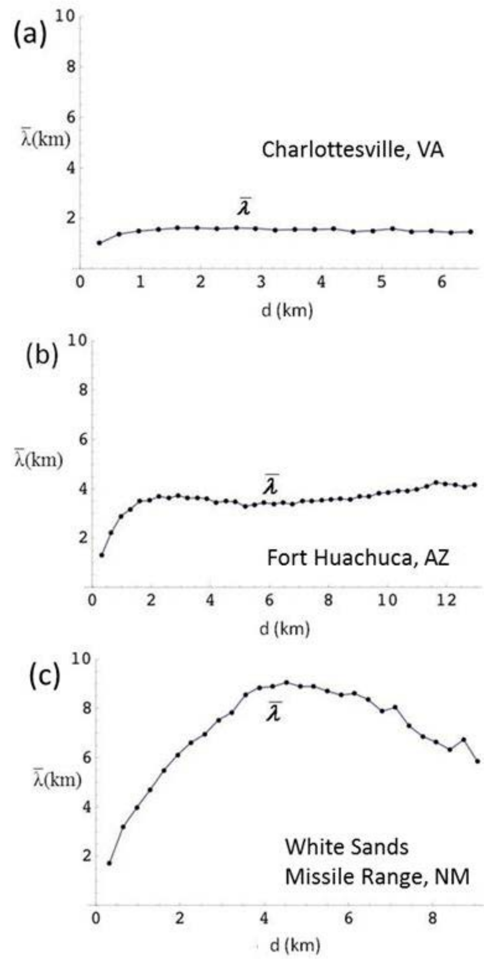


Figure 2-6. Estimating λ at Each of the Binned Values of *d*, by Fitting the Curves for Small Values of δ

Note for Figure 2-6: λ is the characteristic length scale over which changes occur to the connectivity matrix and is approximately constant over the distances shown for Charlottesville (a) and Fort Huachuca (b), indicating that an average value is sufficient to characterize the region. λ for WSMR (c) shows more variation than that for Charlottesville or Fort Huachuca; however, it only varies ±20% between 2 and 8 km. Use of an average value to characterize the WSMR region may still provide useful insights.

3. Discussion

A. Rates of Change

Node mobility in any wireless network is likely to cause the link state to change. Realistic expectations of the rate at which changes occur can inform the selection and/or tuning of a routing algorithm. The probability that a closed link will open for an infinitesimal random spatial node displacement δ is ${}^{\bar{q}\delta}/_{\bar{\lambda}}$. (For the average values to be preserved, the probability of opening must be proportional to $\bar{q}$, and the probability of closing must be proportional to $\bar{p}$.) This probability becomes a time rate of change by taking the first time derivative ${}^{\bar{q}v}/_{\bar{\lambda}}$, where v is the velocity of a node.

A key factor concerning the choice of the routing algorithm is rate of convergence. If link state changes faster than the convergence of the routing algorithm, no benefit is realized in trying to keep pace with the link state. Table 3-1 shows the metrics $\bar{p}$, $\bar{q}$, and $\bar{\lambda}$, based on average features of the terrain for each of the three selected sites.

Table 3-1. The Metrics $\bar{p}$, $\bar{q}$, and $\bar{\lambda}$ Based on Average Features of the Terrain for Each of the Three Selected Sites

	Range Limits		
Site	$\bar{p}$	$\bar{q}$	$\bar{\lambda}$ (km)
Charlottesville (>2 km)	0.1	0.9	1.5
Fort Huachuca (>2 km)	0.4	0.6	4
WSMR (2–6 km)	0.2	0.8	7

Turning this average rate around, we can identify the probability that a given displacement will result in a change in link state. For example, a displacement of $\delta = {}^{\bar{\lambda}}/_{(10\,\bar{q})}$ will result in a 10% probability that a closed link will become open. For Charlottesville, where $\bar{p}$ is 0.1 and $\bar{\lambda}$ is 1.5 km, $\delta_{10\%}$= 170 m. For Fort Huachuca, where $\bar{p}$ = 0.4 and $\bar{\lambda}$ is 4 km, $\delta_{10\%}$ = 660 m (about four times farther than that for Charlottesville).

B. Changes to the Link-State Matrix as a Function of δ

In a MANET, a link-state matrix describes which node pairs are connected by closed links. The nodes use this information to route messages through the network. As link states change, the set of available paths in the network will change. In any mobile

network, the routing table(s) will require periodic updates. The content of these updates will depend on the visibility between nodes and other factors specific to the routing protocols. Different routing protocols handle this procedure differently and may need to take into account details of the expected changes based on terrain.

As we did previously, we will focus on LOS visibility and will use the metrics based on average features to explore how changes to the link-state matrix occur with mobility. We will not attempt to analyze any specific routing procedure; rather, we will characterize the network behavior. We have previously established a metric that describes the characteristic length scale over which nodes typically move before changes to the link state occur. Now, we will look at the extent of changes to the connectivity matrix as a function of displacement.

In terms of specific links, the cases of interest are those where the links are initially closed. Therefore, we compute the probability that visibility will be lost (i.e., a closed link will open as one of the nodes is moved). We use a uniform random laydown of two nodes as the initial state, as was done for the computation of $\lambda(d)$. We select only those pairs where the nodes are connected. We displace one of the nodes in a pair a distance δ in a random direction and evaluate the new link state. We then compute the probability that the link has opened, as a function of δ. Figure 3-1 shows the results for the three regions of interest. In this figure, the displacement is presented in units of $\bar{\lambda}$ for each site. Each point represents the fraction of links that change state for a displacement of the specified magnitude (within a narrow bin about the point) in a random direction.

The Markov model predicts the curves to smoothly approach the value of $\bar{q}$ for the site, by about $2\,\bar{\lambda}$. We use the characteristic value $\bar{\lambda}$ from Table 3-1, which was determined by the rate at which open links close at short separation, to estimate the large separation behavior of the probability that closed links are now open. The results are consistent. The probability that an initially closed link will be open after significant mobility is reasonably well predicted by the rate at which closed links open at the onset of mobility. (Limiting values are .92 (Figure 3-1) vs. .9 (Table 3-1) for Charlottesville; .62 vs. .6 for Fort Huachuca; and .86 vs. .8 for WSMR.) Thus, the terrain can be characterized in terms of average probability of link closure and a length scale for changing state when describing mobile nodes and when describing a static network. We will explore this characterization further. Here, we note that sampling the data indicates that if one of a pair of connected nodes moves by $2\,\bar{\lambda}$, in all three cases, the probability of the link remaining closed drops below 50%.

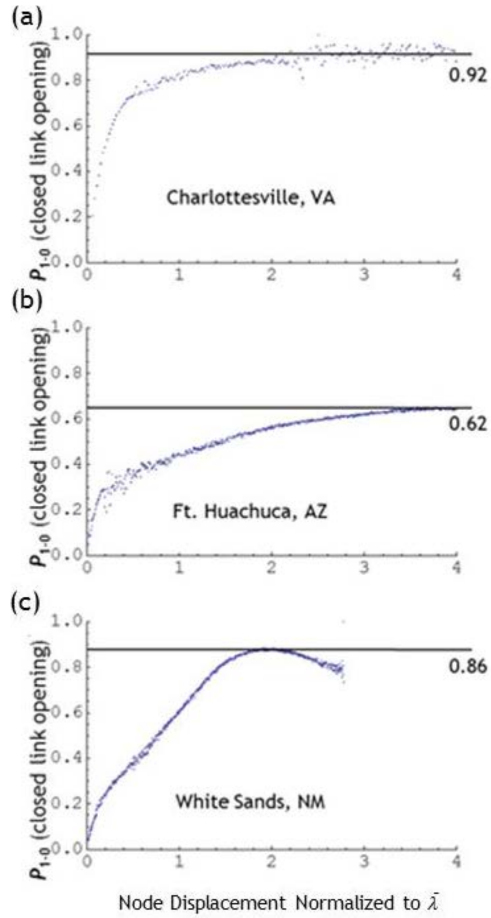
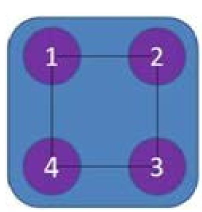


Figure 3-1. The Probability of an Initially Closed Link State Becoming Open as One of the Nodes Is Displaced

Note for Figure 3-1: This probability is shown as a function of the displacement δ, normalized to $\bar{\lambda}$,the characteristic length scale.

C. Effects on the Routing Table

As described previously, for small displacements, the average spatial rate at which a closed link opens is $\bar{q}/\bar{\lambda}$. Similarly, the rate at which an open link closes is $\bar{p}/\bar{\lambda}$. We would like to consider the effect of changes in the link visibility state on the particular routes in a routing table. For simplicity, we describe a small network and discuss the extrapolation to higher number of nodes. Consider a 4-node network, with each of the four nodes connected to two others in a ring:



$$\begin{pmatrix} 1 & 1 & 0 & 1 \\ 1 & 1 & 1 & 0 \\ 0 & 1 & 1 & 1 \\ 1 & 0 & 1 & 1 \end{pmatrix} \tag{3-1}$$

The matrix in Eq. 3-1 displays the connectivity matrix for this network. There are two features to note.

- First, more than one routing table establishes a single network based on this connectivity: 1 and 3 can be connected through either 2 or 4, and 2 and 4 can be connected through either 1 or 3, as shown in the following sample routing tables:

$$\begin{pmatrix} - & \mathbf{1} \rightarrow \mathbf{2} & \mathbf{1} \rightarrow \mathbf{2} \rightarrow \mathbf{3} & \mathbf{1} \rightarrow \mathbf{4} \\ \mathbf{2} \rightarrow \mathbf{1} & - & \mathbf{2} \rightarrow \mathbf{3} & \mathbf{2} \rightarrow \mathbf{3} \rightarrow \mathbf{4} \\ \mathbf{3} \rightarrow \mathbf{2} \rightarrow \mathbf{1} & \mathbf{3} \rightarrow \mathbf{2} & - & \mathbf{3} \rightarrow \mathbf{4} \\ \mathbf{4} \rightarrow \mathbf{1} & \mathbf{4} \rightarrow \mathbf{3} \rightarrow \mathbf{2} & \mathbf{4} \rightarrow \mathbf{3} & - \end{pmatrix},$$

(3-2)

$$\begin{pmatrix} - & \mathbf{1} \rightarrow \mathbf{2} & \mathbf{1} \rightarrow \mathbf{4} \rightarrow \mathbf{3} & \mathbf{1} \rightarrow \mathbf{4} \\ \mathbf{2} \rightarrow \mathbf{1} & - & \mathbf{2} \rightarrow \mathbf{3} & \mathbf{2} \rightarrow \mathbf{1} \rightarrow \mathbf{4} \\ \mathbf{3} \rightarrow \mathbf{4} \rightarrow \mathbf{1} & \mathbf{3} \rightarrow \mathbf{2} & - & \mathbf{3} \rightarrow \mathbf{4} \\ \mathbf{4} \rightarrow \mathbf{1} & \mathbf{4} \rightarrow \mathbf{1} \rightarrow \mathbf{2} & \mathbf{4} \rightarrow \mathbf{3} & - \end{pmatrix},$$

and so forth.

- Second, even though only two-thirds of the possible links are closed, a single network with multiple pathways emerges. This example is a particular illustration of how powerfully an ad hoc network can overcome open links: For 4 nodes with $p = 2/3$, there is a greater than 85% probability all 4 will be connected in a single network. For larger node numbers, low values of p support a high probability of forming a single network while stationary.

We want to quantify the probability that the paths in the original routing table are still valid after the nodes have been displaced. For a MANET, we want to know how the connectivity matrix remains correlated after moving a distance greater than the characteristic length scale for a given terrain. We compute the asymptotic limit approached as mobility becomes equivalent to a redraw of the pair-wise links (which has the same average p). For this specific example, given the previous initial link-state matrix, the average probability of a route still being closed after mobility is given by the probability that the nodes were connected by a single hop (2/3) *multiplied* by the probability that the hop is preserved ($\bar{p}$) *plus* the probability that the nodes were connected by two hops (1/3) *multiplied* by the probability that both hops are preserved ($\bar{p}^2$), or

$$ {}^{2}\!/_{3}\,\bar{p} + {}^{1}\!/_{3}\,\bar{p}^{2}. \tag{3-3}$$

For arbitrary p and q, this probability becomes

$$p\bar{p} + q\bar{p}^{\,2} = \bar{p}^{\,2}(1 + \bar{q})$$

$$\text{for } p = \bar{p}. \tag{3-4}$$

In this case, the initial p was made equal to $\bar{p}$ by hand, but this feature is not required. If we assume that the initial configuration can be any of the $2^6 = 64$ possible combinations of open and closed links between four nodes, weighted by their likelihood, we arrive at the more general results for four nodes.

The probability, P_{ij}, that nodes i and j are initially connected is

$$P_{ij} = p + qp^2(p^2 + 4qp + 2q^2 + 2q^2p), \tag{3-5}$$

and the probability that the connection existed and is preserved is

$$P_{ij} = p^2 + qp^4(p^2 + 4qp + 2q^2 + 2q^2p). \tag{3-6}$$

As the number of nodes (n) increases, the exact expression becomes more complicated. Deducing these relationships by enumeration becomes prohibitive. We are unaware of any closed form expressions but derived a recursion relationship, the details of which will be presented in another forum. In our numerical results, we use this exact solution; however, a simple accurate approximation is valid for the cases of interest. The probability $P_{2\ hops}$ of two nodes being connected by one or more two hop paths but not connected directly is

$$P_{2\text{ hops}} = (1-p)(1-(1-p^2)^{n-2}). \tag{3-7}$$

Therefore, the probability of being connected by one or two hops is

$$\begin{aligned} P_{1\text{ or }2\text{ hops}} &= p + (1-p)(1-(1-p^2)^{n-2}) \\ &= 1-(1-p)(1-p^2)^{n-2}, \end{aligned} \tag{3-8}$$

and the probability that the nodes will remain connected after mobility is

$$P_{\text{preserved}} = p^2\,(1+q)(1-(1-p^2)^{n-2}). \tag{3-9}$$

This expression will underestimate the probability of paths remaining closed because it neglects paths with three or more hops as their shortest path. The underestimate is very small: If p is large, nodes are connected by one or two hops, and, if p is small, the high powers of p needed to preserve paths reduce the contribution of long pathways.

The large n limit reduces to

$$P_{\text{preserved}}\ (n\ large) \rightarrow \bar{p}^{\,2}(1+\bar{q}), \tag{3-10}$$

which is also the expression for n = 4 in the special case where we ensured that all the nodes were initially connected by one or two hops.

The implications of this result are significant. We saw earlier that even relatively low values of $\bar{p}$ (e.g., around one-half at Fort Huachuca) lead to a fairly high probability of fully connected static networks. This result is supported by simulations intended to measure the resilience of static networks to the loss of individual nodes (Newman 2008). However, low values of $\bar{p}$ will lead to rapid loss of connectivity during mobility, which is illustrated in Figure 3-2. This figure compares the probability of obtaining connectivity between two nodes with the probability that the connectivity is preserved after moving a couple of characteristic lengths.

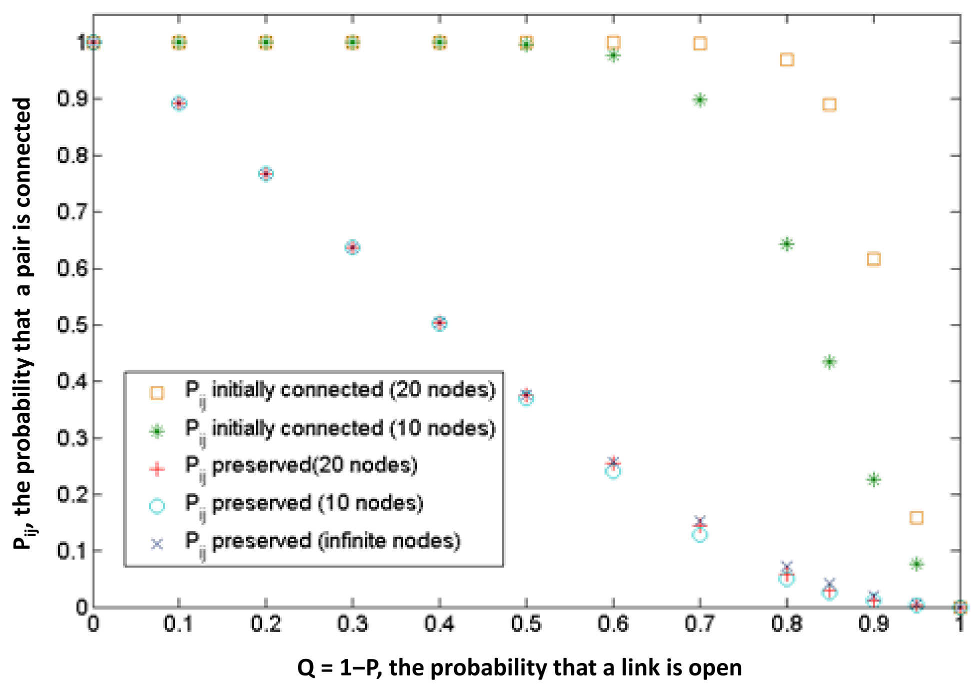


Figure 3-2. The Probability of Obtaining Connectivity between Two Nodes vs. the Probability That the Connectivity Is Preserved after Moving a Couple of Characteristic Lengths

Note for Figure 3-2: This figure shows how the initial probability that a pair of nodes will be connected falls as the average probability that pairwise links are closed falls. The networks remain nearly completely connected until the probability of an open link is well above 60%. Also shown is the probability that a pair of nodes will remain connected via the same path after mobility sufficient to randomize the pair-wise links, typically a couple of length scales. This probability that a pair of nodes will remain connected, in contrast, falls rapidly as the probability of open links increases.

Note that for both 10 and 20 nodes, essentially complete connectivity is maintained even for low values of p. Increasing the number of nodes from 10 to 20 extends the 90% connectivity from p of 30% down to p of 15%. However, the probability of preserving connections falls quite fast with decreasing p and is nearly independent of n. The $n = 10$ case is barely distinguishable from the infinite n case. Increasing the number of nodes increases the probability of initial connectivity. However, the probability that a particular path in the routing table will be preserved does not increase significantly as a function of the number of nodes in the network.

These results only confirm what one would logically expect. However, the utility offered by this analysis is that averaged properties of the terrain can quantitatively inform the expected evolution of network topology during mobility. In particular, we have shown that terrain features that support static networks may not support rapidly moving networks. Further, some terrain features, which we have captured as an average length scale, affect mobile networks but do not affect static networks.

4. Summary

Terrain features pose a challenge for the implementation of MANETs. We show that modern terrain databases and computational tools allow one to display and characterize readily the features that will affect a MANET.

We chose three distinct regions and used contour maps to generate maps of probability of point-to-point LOS (a surrogate for link closure) for various range bins. This analysis provides a glimpse of the terrain challenges for MANET operation. For two of the three terrain types we examined, we found that the probability of LOS between two points is relatively insensitive to separation.

Mobility of the nodes will change the LOS probabilities continuously. We computed the changes to the connectivity matrix over time with mobility. This computation allows one to determine a rate of change of link state (due to LOS). This rate of change with node mobility is also relatively insensitive to separation, which suggests that insights can be gained from a general treatment of mobility as a Markov process in terms of the average probability of LOS and the characteristic length scale over which changes in LOS occur.

Predictions based on average parameters can be compared with Monte Carlo samplings of the terrain from which the average features were determined. We find that the probability of two connected nodes remaining connected falls rapidly as the LOS probability decreases. Further, this falloff is nearly independent of node number. The mobile case is in contrast to the static case, where the initial laydown for any link probability can be made highly connected by adding nodes. When mobile, the additional nodes do not improve the probability that the initial paths between nodes will remain closed.

The characterization of terrain in terms of an average LOS probability and a length scale for changes should prove useful in conceptualizing future approaches to routing in MANETs. Specifically, we believe that a successful routing approach will be informed and responsive to terrain features, as opposed to a unique solution for a limited set of features. In support of that goal, future work will quantify how well treatment in terms of averages compares with Monte Carlo treatments of the real terrain. The terrain types analyzed vary significantly in how well they can be characterized by separation-independent average parameters and may allow some determination of the strengths and limitations of the approach. Figures of merit would include, at a minimum, the number of connected subnets, the average path length, and the probability of two random nodes being connected.

Appendix A.
Calculation of the Terrain Link Closure Maps

This appendix gives details on the calculation of the terrain link closure maps (see Figure 2-3). Our terrain data lie on a regular grid with 30-m spacing. For each geographical locale, we take an operational square 20 km on a side. Let N be the number of points on an edge of the square (N = 666 in this case). Checking line-of-sight (LOS) between two arbitrary points requires checking $O(N)$ points between the two end points. Hence, calculating LOS connectivity between all points—at least in a naïve, brute force approach—in the operational area is of order N^5 operations, which is about 10^{14} in our case.

We simplified the calculation by using a simple Voronoi decomposition of the operational area. This was done by first coarsely gridding the area. We uniformly sampled the grid at 120, 180, or 240 m, which corresponds to a grid cell containing 16, 36, or 64 points of the original 30-m resolution grid, respectively. In each grid cell, the two points with the highest and lowest elevation were selected. The set of all such "seed" points was used to construct a Voronoi partition of the operational area, which is a covering of polygons with each point in a polygon being closer to a seed point than any other seed point. LOS was calculated between all of the seed points. LOS points were binned by distance ranges, and the corresponding polygon was colored according to the fraction of closed links in the bin. We spot-checked these results with exact calculations and found that the error was typically less than 5% of the points in the polygon, with less coarse sampling being more accurate. This method works well because the Voronoi decomposition using the extreme point method typically captures terrain features such as a hill or a depression in a single polygon.

Illustrations

Figures

Table

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Abbreviations

DoD	Department of Defense
LOS	line-of-sight
MANET	Mobile Ad Hoc Network
NED	National Elevation Dataset
SIAM	Society for Industrial and Applied Mathematics
USGS	U.S. Geological Survey
WSMR	White Sands Missile Range

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14. ABSTRACT

This document focuses on performance prediction for a mobile ad hoc network (MANET) in actual terrain, where line-of-sight (LOS) between nodes is used as a proxy for connectivity. We have analyzed three regions that span three different types of terrain and have produced connectivity maps at a variety of ranges. For each of the three sites, we also computed the average probability of link closure as a function of the distance between nodes. The three terrain types chosen differ significantly in how well a single value characterizes the probability of link closure over an extended range of separations. However, we find that even for the most challenging case, many aspects of network behavior can be characterized in terms of a single characteristic probability. The changes in individual link state will occur over a characteristic (average) length scale, and we discovered that this varies slowly as the distance between nodes increases. These results, based on extensive sampling of real terrain, suggest that many features of MANET performance can be accurately described in terms of average parameters, independent of the node separation. In particular, we modeled link closure as a birth-death process (i.e., a Markov process where the state is the number of closed links and the transitions are integer increments (births) or decrements (death)). This type of model lets us estimate the probability that an initial closed path in a network will continue to be closed under mobility, using average properties of the terrain. We found that low pair-wise connectivity does not necessarily impair overall network connectivity when nodes are static but that networks suffer dramatic degradation when nodes become mobile, even of lost LOS is the only cause of lost connectivity. This will occur for ordinary terrain of a type found across much of the world. We have also estimated the length scale over which this degradation will occur based on average features of the terrain.

15. SUBJECT TERMS

mobile ad hoc network (MANET), network connectivity, software-defined radio

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